NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4333

EFFECT OF SOME EXTERNAL CROSSWISE STIFFENERS ON THE HEAT TRANSFER AND PRESSURE DISTRIBUTION ON A FLAT PLATE AT MACH NUMBERS OF 0.77, 1.39, AND 1.98

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EFFECT OF SOME EXTERNAL CROSSWISE STIFFENERS ON THE HEAT TRANSFER AND PRESSURE DISTRIBUTION ON A FLAT PLATE AT MACH NUMBERS OF 0.77, 1.39, AND 1.98[1]

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SUMMARY

An experimental investigation was made to determine the aerodynamic heat transfer and pressure distribution on flat-plate models (50 inches long) with various arrangements of external stiffeners mounted normal to the direction of air flow. The tests were made under steady flow conditions in a free jet at Mach numbers of 0.77, 1.39, and 1.98, with Reynolds numbers of 3×10^6, 7×10^6, and 14×10^6, respectively, based on a length of 1 foot.

At all three Mach numbers, the addition of stiffeners to a flat plate caused large pressure variations and large pressure losses in the flow along the plate. The tests at a Mach number of 1.98 showed that the magnitude of these pressure variations and losses caused by the first four stiffeners remained constant regardless of stiffener height, stiffener spacing, and model scale.

At all three Mach numbers, the heat transfer on the stiffeners, as shown by the Stanton numbers based on free-stream properties, had large variations, the heat transfer being maximum on the upstream surface and decreasing to a minimum on either the top or downstream surface. The tests at a Mach number of 1.98 showed that an increase in stiffener height decreased the average level of the free-stream Stanton numbers on the plate between stiffeners. Other tests at this same Mach number indicated that the average level of the Stanton numbers on the plate between stiffeners remained constant regardless of stiffener spacing or model scale.

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[1]The information presented herein was previously given limited distribution.

INTRODUCTION

In some missile systems, the external wall of the missile serves also as the wall of the fuel tank. In such systems, one proposal for the construction of the missile wall is to use a very thin skin that is stiffened by the combination of internal pressure and external stiffeners. One of the factors affecting the decision to use such an externally stiffened arrangement is the aerodynamic-heating characteristics of the skin. With the heating characteristics known, the strength of the skin can be estimated.

In view of the aforementioned proposal, a program was initiated to determine the effects of adding the stiffener frames, the effect of frame height and spacing, and the effect of scale on the aerodynamic-heating characteristics of the skin. Three flat-plate models simulating the various proposed stiffening arrangements and one flat-plate model with no stiffeners were tested in the 27- by 27-inch nozzles of the preflight jet of the Langley Pilotless Aircraft Research Station at Wallops Island, Va. The tests were performed at sea-level pressure conditions at Reynolds numbers of 3×10^6, 7×10^6, and 14×10^6, based on a length of 1 foot, for Mach numbers of 0.77, 1.39, and 1.98, respectively.

Theoretical methods and test data are presently available for heat-transfer calculations for both plates and bodies in high-speed flow; however, these data are satisfactory only for aerodynamically clean surfaces. The externally stiffened configuration proposed may alter the flow conditions at the surface in such a way that available methods for determining heat-transfer coefficients may not be valid. The tests were made to determine heat-transfer coefficients at various points on the skin and stiffeners, and these heat-transfer coefficients were compared with flat-plate heat-transfer coefficients at similar points. This comparison permitted a direct evaluation of the effects of the external stiffeners on the aerodynamic-heating characteristics of the skin.

SYMBOLS

$c_{p,w}$ — specific heat of skin, Btu/lb-°R

C_p — pressure coefficient, $\dfrac{p_l - p_\infty}{q_\infty}$

R — radius, in.

$c_{p,\infty}$ free-stream specific heat of air at constant pressure, Btu/lb-°R

ρ_w weight density of skin, lb/cu ft

ρ_∞ free-stream weight density of air, lb/cu ft

h local aerodynamic heat-transfer coefficient, Btu/(sec)(sq ft)(°R)

M free-stream Mach number

$N_{St,\infty}$ Stanton number based on free-stream conditions, $\frac{h}{c_{p,\infty}\rho_\infty V_\infty}$

p_l local static pressure, lb/sq ft

p_∞ free-stream static pressure, lb/sq ft

q_∞ free-stream dynamic pressure, lb/sq ft

t skin thickness, ft

τ time, sec

T_{eq} equilibrium temperature, °R

T_t free-stream stagnation temperature, °R

T_w wall temperature, °R

V_∞ free-stream velocity of air, ft/sec

x distance from leading edge of plate, in.

APPARATUS

Models

Drawings of the four plates tested are shown in figure 1. The details of construction and the materials used are shown in the upper portion of the figure. The side views of the four plates with the major dimensions are shown in the lower portion. The plates were 50 inches in length and were made with a 7.417° wedge at the upstream end to simulate the fairing to the supporting structure. The external stiffeners were mounted normal to the direction of the flow.

The hat-shaped stiffeners and the skin to which they were riveted were all made of Inconel. This material was used because, in addition to being a good calorimeter for heat-transfer investigations, it had low conductivity and would thereby reduce conduction effects along the skin. The skin was made thin (0.062 inch) to increase the temperature response of the skin and also to reduce the temperature lag through the skin.

As shown in section A-A (fig. 1) the supporting spacers were placed so as to leave three large open bays over which the skin was isolated from large heat sinks. In order to isolate further the skin from the supporting structure, a sheet of 0.125-inch-thick asbestos was placed under the skin. The skin made contact with the supporting structure through rivets and at its upstream edge.

Each of the four plates had a row of iron-constantan thermocouples (No. 30 gage wire) in the middle of the center bay and a row of static-pressure orifices (0.0625-inch diameter) in one of the side bays. In addition, to permit the heat conduction into the spacers to be determined, a few other thermocouples were mounted on the skin near the spacers.

Test Facility

The investigation reported herein was conducted in the preflight jet of the Langley Pilotless Aircraft Research Station at Wallops Island, Va. The tests were made in the 27- by 27-inch free jet at sea-level pressure conditions for free-stream Mach numbers of 0.77, 1.39, and 1.98. The stagnation temperature for all tests was approximately 935° R. This blowdown jet is more fully described in reference 1.

A photograph of plate IV mounted at the exit of the 27- by 27-inch nozzle is shown in figure 2. The other plates were mounted in the same manner. The leading edge of the plate was positioned approximately $8\frac{1}{2}$ inches upstream of the nozzle exit. The center line of the plate coincided with the center line of the nozzle. In this position, the major portion of the plate was in the homogeneous flow field from the nozzle.

As shown in figure 2, extensions were bolted to the upper and lower nozzle plates to support the plate on which heat transfer was to be determined. The thermocouple leads and the pressure tubes can be seen extending from the rear of the plate.

PROCEDURE

Tests

At the beginning of each blowdown test, there was a period of about 2 seconds during which the pressure and temperature of the jet were transient. The pressure and temperature then became steady and were maintained nearly constant for periods of 8, 18, and 36 seconds at Mach numbers 1.98, 1.39, and 0.77, respectively, after which time the required free-stream total pressure could not be maintained because of the exhaustion of the air from the storage spheres. These pressure and temperature measurements were time correlated by oscillograph recorders.

All four plates were tested at Mach numbers of 1.98 in order to determine the effects of adding the stiffener frames, the effect of frame height and spacing, and the effect of scale on the aerodynamic heating characteristics. Plates I and II were also tested at Mach numbers of 0.77 and 1.39 in order to determine the effect of Mach number.

The tests were performed at zero angle of attack at sea-level pressure conditions at Reynolds numbers of 3×10^6, 7×10^6, and 14×10^6, based on a length of 1 foot, for Mach numbers of 0.77, 1.39, and 1.98, respectively. The free-stream total temperature for all tests was approximately 935° R, which is the total temperature for a Mach number of 1.98 at standard sea-level conditions. This temperature was used for all tests, including those at Mach numbers of 0.77 and 1.39, in order to assure that the temperature forcing function $T_{eq} - T_w$ and the temperature-time derivative $dT_w/d\tau$ would be of sufficient magnitude to assure fair accuracy in the data reduction.

Reduction of Data

The aerodynamic heat-transfer coefficients were calculated from data measured during the transient heating of the plate after the establishment of steady air flow from the nozzle. Radiation from the plate surface and conduction into the internal structure were found to be negligible. Conduction along the surface in a streamwise direction was also negligible except for the stiffeners. On the stiffeners, estimates indicated that conduction was probably of the order of 10 percent of the convective heat transfer in several cases; however, there were insufficient measurement points to determine this conduction with a satisfactory degree of accuracy. Therefore, the convective heat-transfer coefficients are presented for all measurement points on the models without attempt to make conduction corrections. It is believed that the heat-transfer coefficients on the flat-plate surfaces of the models are probably accurate to within 15 percent, whereas those on the stiffeners are probably accurate to within 25 percent.

Neglecting radiation and conduction, the convective heat transferred to the model can be equated to the heat absorbed by the model skin per unit of time. This relation is expressed in the following equation:

$$h\left(T_{eq} - T_w\right) = \rho_w c_{p,w} t \frac{dT_w}{d\tau}$$

The aerodynamic heat-transfer coefficient h was evaluated by using the weight density ρ_w of the Inconel skin as 518 pounds per cubic foot and its specific heat as given in reference 2. The skin thickness t at all thermocouple stations was 0.062 inch.

The skin temperature and its rate of change with time were obtained from the measured time histories of the skin temperature. A typical skin-temperature and stagnation-temperature time history for each Mach number is shown in figure 3. This figure shows that both the rate of change of wall temperature $\frac{dT_w}{d\tau}$ and the temperature forcing function $T_{eq} - T_w$ were of similar magnitude for each test Mach number at the time (approximately 5 seconds) when the Stanton numbers were determined.

The equilibrium wall temperature at each thermocouple was obtained by plotting the temperature against the slope of the temperature-time curve and by extrapolating this curve to the equilibrium wall temperature which would occur at zero slope. These temperature slope curves were best faired and extrapolated with straight lines, which indicated that the heat-transfer coefficients were essentially constant with wall temperature. Since the heat-transfer coefficients were essentially constant, they are only presented for one time during each test. The values of wall temperature at which these heat-transfer data are presented are given in table I.

RESULTS AND DISCUSSION

Pressure Distributions

The pressure coefficients for the four plates are presented at the top of figures 4 to 9. The locations of the pressure orifices on the stiffeners are as shown in figure 1. The locations of those on the flat part of the models were not given in figure 1, but are indicated by means of the datum points in figures 4 to 9.

As expected, the pressures on the flat-plate model (plate I, fig. 4) did not vary appreciably from the free-stream static pressure. However, the pressures on the models with stiffeners (figs. 5 to 9) did vary considerably. A rise in pressure occurred upstream of each stiffener and reached a maximum on the upstream face of the stiffener. The pressure decreased rapidly downstream of each maximum pressure point and reached a minimum at different points, with the minimum depending on the free-stream Mach number and on the number of stiffeners over which the flow had progressed. The pressure data indicate that the addition of stiffeners to a flat plate at all three Mach numbers caused large pressure losses in the flow along the plate since, in general, the magnitude of the pressure variations decreased for each succeeding stiffener as the flow progressed downstream.

Effect of stiffener height.- By comparing the pressures for plate II (fig. 7) and plate III (fig. 8), it will be noted that at a Mach number of 1.98 the increase in height of the stiffeners from 0.4 inch to 1 inch did not noticeably change the magnitude of the pressure variations. Likewise, this increase in height of the stiffeners did not change the location of the maximum and minimum pressures. The pressures downstream of the stiffeners indicated, however, that the high stiffeners influenced the pressures farther downstream. It is probable also that the high stiffeners influenced the pressures farther upstream, although there were insufficient measurement points to confirm this.

Effect of stiffener spacing.- By comparing the pressures for plate II (fig. 7) and plate IV (fig. 9), it will be noted that at a Mach number of 1.98 decreasing the spacing of the small stiffeners from 11.725 inches to 4.690 inches did not noticeably change the magnitude of the pressure variations. Also, this decrease in spacing of the stiffeners did not significantly change the extent of the downstream pressure influences. The 4.690-inch spacing of the stiffeners was equal to or less than the distance sufficient to eliminate the constant-pressure region which probably existed between the wider spaced stiffeners.

As mentioned previously, the magnitudes of the pressure variations were, in general, a function of the number of stiffeners over which the flow had progressed. Thus, at a Mach number of 1.98, the greater number of stiffeners in a given length produced the greater pressure losses in the flow along the plate. This is substantiated by comparing the magnitude of the pressure variations for plate IV (fig. 9) with those for plate II (fig. 7).

Effect of scale.- By comparing the pressures for plate III (fig. 8) and plate IV (fig. 9), the effect of changing the model scale can be determined. Plate III is not exactly a scaled version of plate IV since the shape of the stiffener is somewhat different and since the length of plate upstream of the first stiffener was the same for both. If these two departures from geometric similarity are neglected, however, the effect of scale can be determined. By comparing the pressures in the region of the first four stiffeners on each plate, it can be seen that at a Mach number of 1.98 the pressure variations are of about equal magnitude at the same scaled positions. It may be concluded that increasing the scale within this range did not increase the pressure losses.

Equilibrium Temperatures

The experimental equilibrium temperature ratios for the four plates are are also shown in figures 4 to 9. As stated previously, the values were obtained by plotting the slope of the temperature-time curves against wall temperature and by extrapolating to zero slope.

The equilibrium temperatures on the plates with stiffeners had considerable scatter. Hence, instead of attempting to fair the data with connecting curves, only partial-span straight lines were drawn between the data points to help to give continuity. There were some thermocouples during each test that were inoperative and caused deficiencies in the data where the data were greatly needed. Where these data points were not obtainable, the straight line between data points was omitted to emphasize the discontinuity of the data at these places.

In all tests in which the small stiffeners were used, the equilibrium temperatures were generally highest on the top of the stiffeners. For some reason the equilibrium temperatures on the second stiffener of plate II did not follow this pattern when tested at a Mach number of 1.39. In the test in which the large stiffeners were used, the equilibrium temperatures were highest on the upstream face of the stiffeners and lowest on the downstream face.

The equilibrium temperatures as plotted in these figures show that the temperature gradients would generally have been very large on the stiffeners if the tests had continued long enough for the temperature gradients to reach equilibrium. Also, at some points on the flat-plate portions of the models, the temperature gradients would have been fairly large at equilibrium. If no streamwise conduction had existed, the variation in these equilibrium temperatures would have been even greater than shown; that is, the high equilibrium temperatures would have been somewhat higher and the low equilibrium temperatures would have been somewhat lower.

Heat Transfer

The heat transfer on the four plates for all tests is presented in the form of Stanton number. Since local flow conditions could not be determined on the plates with stiffeners, the Stanton numbers are based on free-stream conditions. On plate I (no stiffeners) the local and free-stream flow conditions were almost identical. Hence, on this plate, the Stanton numbers can be considered to be based on either local or free-stream conditions depending on the comparison needed. This flat plate was tested to determine the heat transfer on a flat plate in the preflight jet, and hence to provide a basis on which to compare the heat transfer of the other three plates.

As mentioned previously, the large conduction effects that were present on the stiffeners made the Stanton numbers shown for the stiffeners very inaccurate. However, a qualitative determination of the effects of the stiffeners on the heat transfer can still be obtained. Also, as discussed in the section entitled "Equilibrium temperatures," some of the thermocouples on the stiffeners were inoperative during each test and caused deficiencies in the data where the data were greatly needed. Where these Stanton numbers could not be obtained on the stiffeners, the straight lines between data points were omitted to emphasize the discontinuity of the data at these points.

Effect of stiffeners.- On the flat plate in figure 4, the dashed curves shown on the Stanton number plots are curves calculated by the Van Driest flat-plate turbulent theory. (See ref. 3.) The turbulent-theory curves and the data obtained were in good agreement. These theory curves were a good fairing of the actual data and were superposed on the data of the other plates (figs. 5 to 9) so that a heat-transfer comparison could be made between the flat plate and the plates with stiffeners.

As shown in figure 5, the addition of stiffeners at a Mach number of 0.77 caused the Stanton numbers on the flat portion of the plate to be generally much greater than for the plate without stiffeners. Figure 6 shows that the addition of these same stiffeners at a Mach number of 1.39 caused the Stanton numbers on the flat portions of the plate to be generally slightly greater, whereas figure 7 shows that the addition of these same stiffeners at a Mach number of 1.98 made practically no change in the Stanton numbers on the flat portions of the plate.

The Stanton numbers on the stiffeners at all three Mach numbers had some very large variations. On the front face of the stiffener, the Stanton number was almost always greater than at any other place on the stiffener. From these maximum values on the front face, the Stanton numbers decreased downstream to a minimum value on the top or downstream surface of the stiffener. The location on the stiffeners at which the minimum Stanton numbers occurred did not appear to be consistent.

Effect of stiffener height.- The effect of stiffener height on Stanton number at a Mach number of 1.98 can be noted by comparing the Stanton number plots at the bottom of figures 7 and 8. No definite comparisons can be made between the maximum magnitude in Stanton numbers which occurred on the stiffeners. Some of the data on stiffeners that would have helped in making this comparison were not obtained.

One comparison that can be made between these two configurations is the effect of stiffener height on the flat-plate Stanton numbers. Figure 7 shows that, even though the Stanton numbers on the stiffeners had large variations, these stiffeners had no noticeable effect on the Stanton number average for the flat-plate portions. The scatter of the data for the flat plate between stiffeners apparently is no greater than that for the flat plate without stiffeners. Figure 8, however, shows that the higher stiffeners caused a considerable deviation in the flat-plate Stanton numbers compared with the Stanton numbers for the plate without stiffeners. This result is consistent with the comparison of pressure coefficients in figures 7 and 8, which indicated that the higher stiffeners disturbed the flow over more of the plate than did the low stiffeners. This disturbed flow caused by the higher stiffeners seemed to be favorable in that the Stanton numbers between stiffeners were, in general, somewhat lower than flat-plate values.

Effect of stiffener spacing.- As noted in the previous section, a good comparison between the Stanton numbers on the stiffeners at a Mach number of 1.98 cannot be determined because of the lack of data at important points and because of the erratic nature of the data on the stiffeners. Hence, only the effect of stiffener spacing on the flat-plate Stanton numbers is discussed.

In comparing figures 7 and 9, it appears that a decrease in spacing did not change the Stanton number average on the flat plate between stiffeners but did cause the data to be more erratic. This may be due to the fact that a pressure gradient existed on the flat plate between stiffeners at this close spacing. At the greater spacing shown in figure 7, the pressure gradient on the flat plate between stiffeners was doubtless near zero for the major portion of the spacing.

Effect of scale.- Plate III is a scaled-up model of the height and spacing of the first four stiffeners of plate IV. The actual shape of the stiffener is slightly different and the length of plate upstream of the first stiffener was not scaled up. If these two departures from geometric similarity are neglected, then the effect of scale can be determined.

By comparing the pressure coefficients in figures 8 and 9, it appears that the flow is somewhat similarly disturbed for the full distance between stiffeners for the two different scale models. Hence, as expected, the Stanton number average between stiffeners for these two models at a Mach number of 1.98 is about the same. However, the local Stanton numbers for the small-scale model (fig. 9) did appear to be more erratic between stiffeners.

CONCLUSIONS

An experimental investigation was made in a free jet at Mach numbers of 0.77, 1.39, and 1.98 to determine the aerodynamic heat transfer based on free-stream properties and the pressure distribution on models with various external-crosswise-stiffener arrangements. The following conclusions can be made:

1. The addition of stiffeners to a flat plate at all three Mach numbers caused large pressure losses in the flow along the plate.

2. At a Mach number of 1.98, the greater number of stiffeners in a given length produced the greater pressure losses in the flow along the plate.

3. At a Mach number of 1.98, the magnitude of the pressure variations caused by the first four stiffeners remained constant regardless of stiffener height, stiffener spacing, and model scale.

4. At all three Mach numbers, the Stanton numbers on the stiffeners had large variations, being maximum on the front face and decreasing to a minimum on either the top or downstream surface.

5. At a Mach number of 1.98, an increase in stiffener height decreased the average level of the Stanton numbers on the plate between stiffeners.

6. At a Mach number of 1.98, the average level of the Stanton numbers on the plate between stiffeners remained constant regardless of stiffener spacing or model scale.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 14, 1957.

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TABLE I

VALUES OF WALL TEMPERATURE AT WHICH STANTON NUMBERS ARE PRESENTED

Plate I

x, in.	T_w, °R		
	M = 0.77	M = 1.39	M = 1.98
3.9	706	711	698
8.5	704	722	710
13.5	696	724	708
18.5	688	721	706
23.5	693	718	710
28.5	672	693	701
33.5	686	735	706
38.5	678	708	698
43.5	672	719	688
48.5	663	711	693

Plate II

x, in.	T_w, °R		
	M = 0.77	M = 1.39	M = 1.98
3.8	731	734	693
5.0	738	769	714
6.8	732	765	731
*8.5	650	692	665
10.1	707	789	732
11.8	746	780	723
15.8	748	797	731
18.5	740	819	763
*19.9	768	846	818
*20.1	750	774	731
*20.3	717	712	---
21.6	764	807	742
23.5	754	775	723
27.5	731	777	723
30.2	715	778	734
*31.6	702	731	---
*31.8	752	823	802
*32.0	723	764	709
33.5	764	789	729
35.2	---	781	711
39.2	710	770	712
41.8	705	752	716
*43.3	717	765	724
*43.5	739	798	786
*43.7	692	731	648
45.0	756	792	715
46.8	738	783	698
48.8	706	700	685

Plate III

x, in.	T_w, °R
	M = 1.98
3.7	704
5.0	719
6.8	741
*7.9	811
*8.9	619
9.8	685
11.8	731
15.8	748
18.5	754
*19.5	824
*20.0	732
*20.5	645
21.6	694
23.5	729
27.5	728
30.2	736
*31.3	803
*31.8	692
*32.3	647
33.5	663
39.5	715
42.0	718
*43.0	803
*44.0	657
45.0	652
47.0	666
49.0	667

Plate IV

x, in.	T_w, °R
	M = 1.98
3.8	680
5.0	731
6.8	733
*8.2	822
*8.4	743
*8.6	679
10.0	737
11.5	768
*12.8	815
14.5	769
16.2	758
*17.6	813
*17.8	743
*18.0	723
19.2	742
20.9	744
*22.2	814
*22.4	722
*22.6	703
24.0	720
25.6	728
*26.8	785
*27.0	728
*27.2	724
28.5	726
30.2	719
*31.6	793
*31.8	727
*32.0	676
33.5	723
38.4	699

*Measuring station on stiffener.

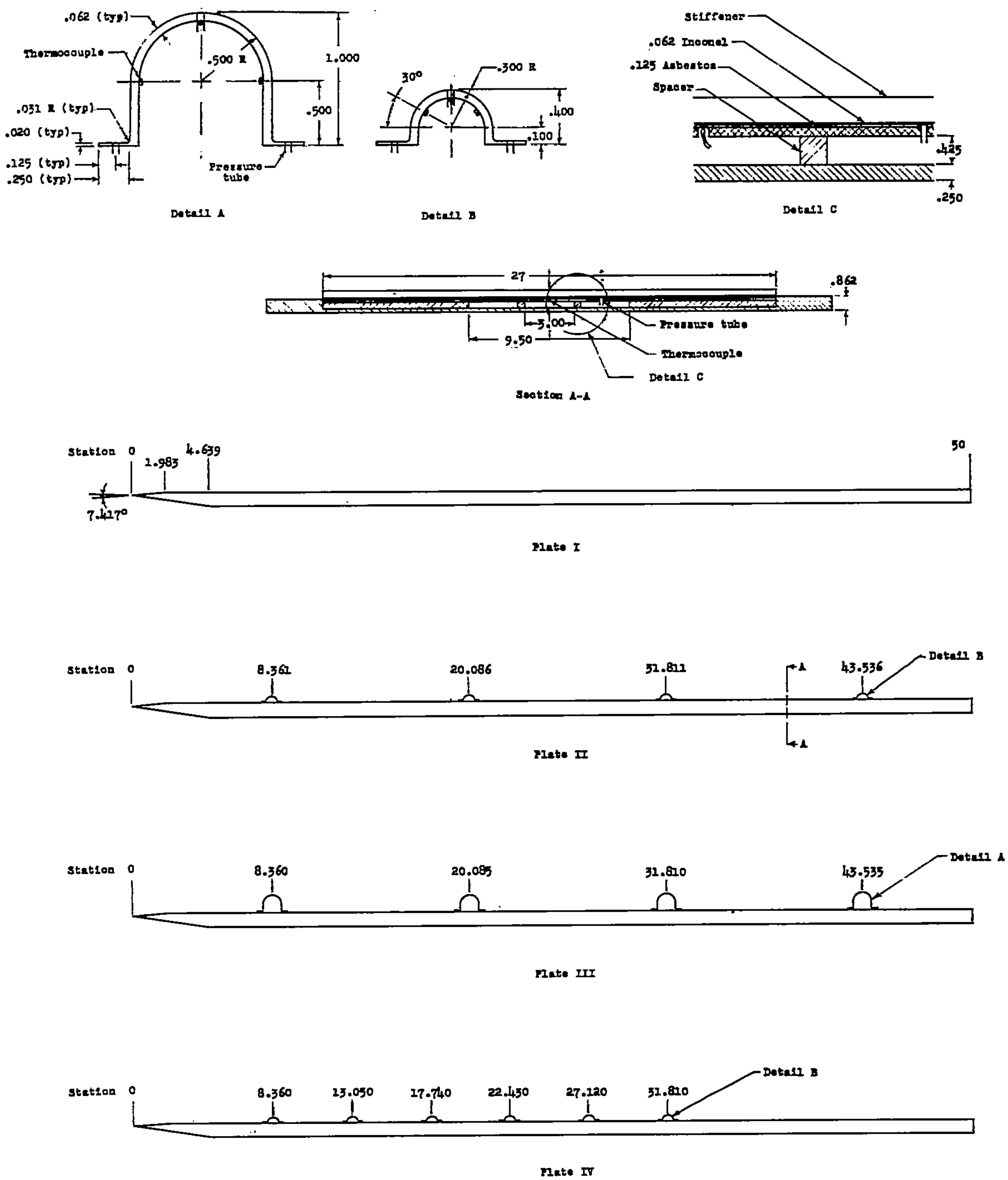

Figure 1.- Drawings of four plates investigated. All dimensions are in inches.

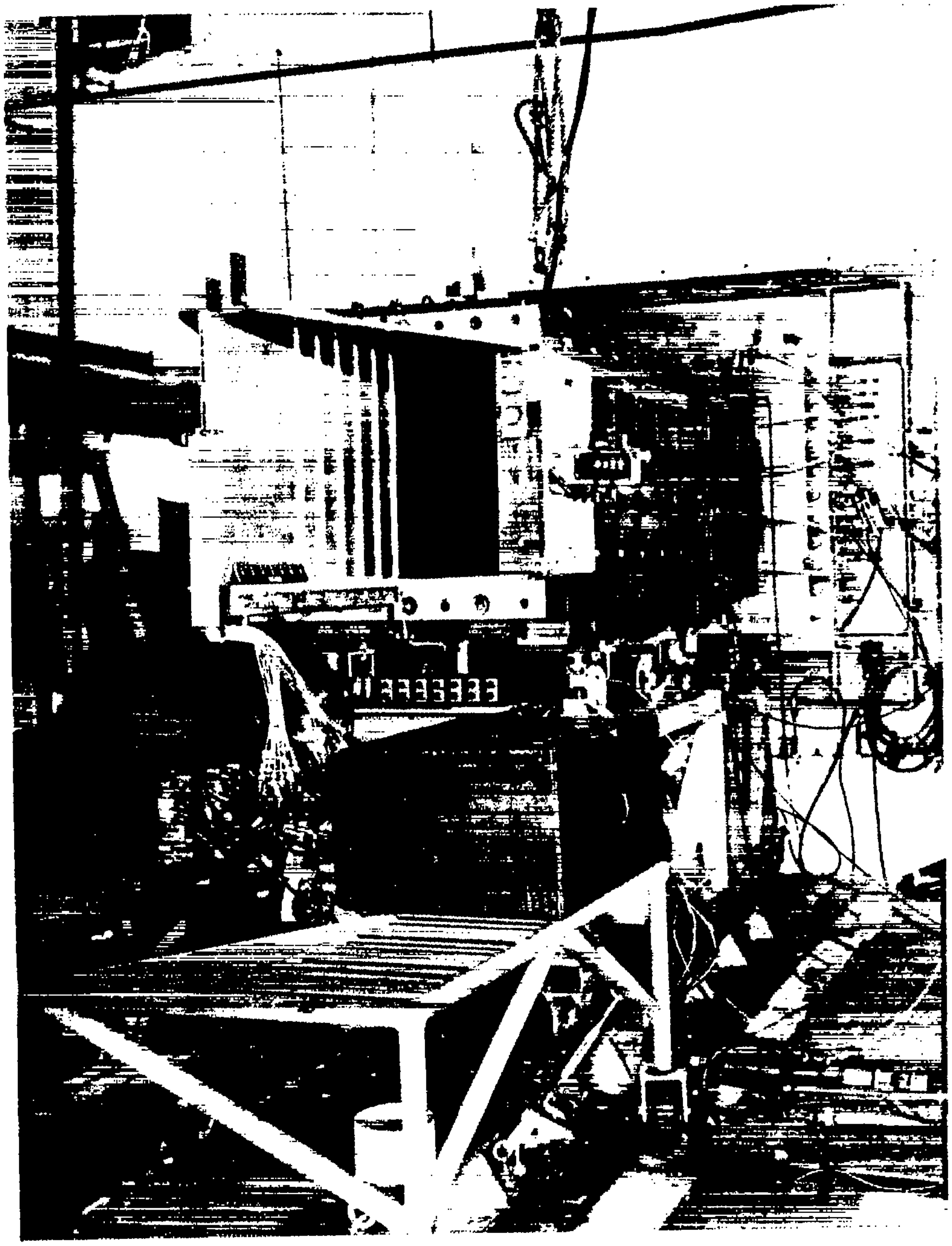

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Figure 2.- Photograph of plate IV mounted at exit of 27- by 27-inch nozzle in preflight jet of Langley Pilotless Aircraft Research Station at Wallops Island, Va.

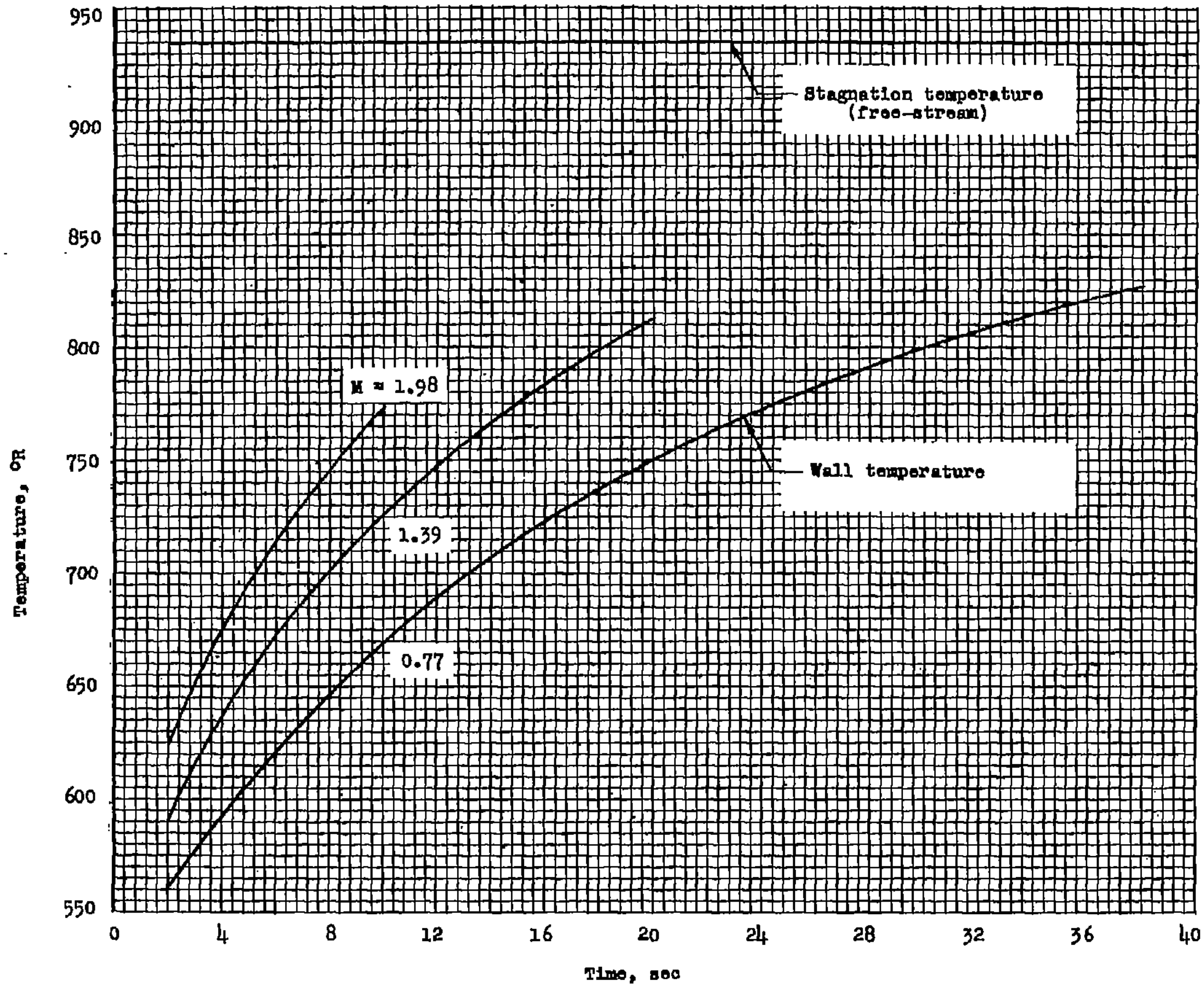

Figure 3.- Typical temperature time histories for three Mach numbers.

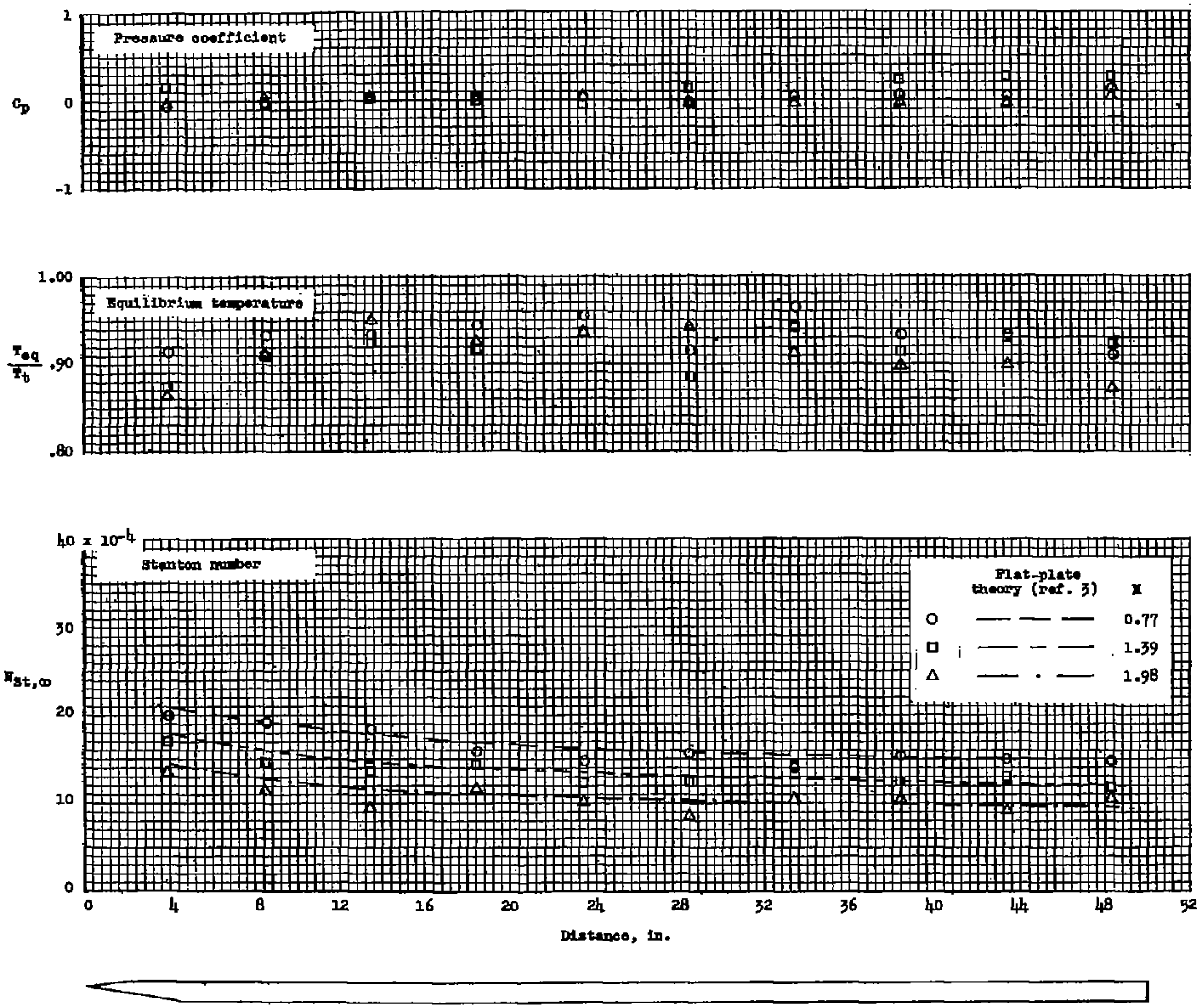

Figure 4.- Distribution of heat-transfer parameters and pressures for plate I at M = 0.77, 1.39, and 1.98.

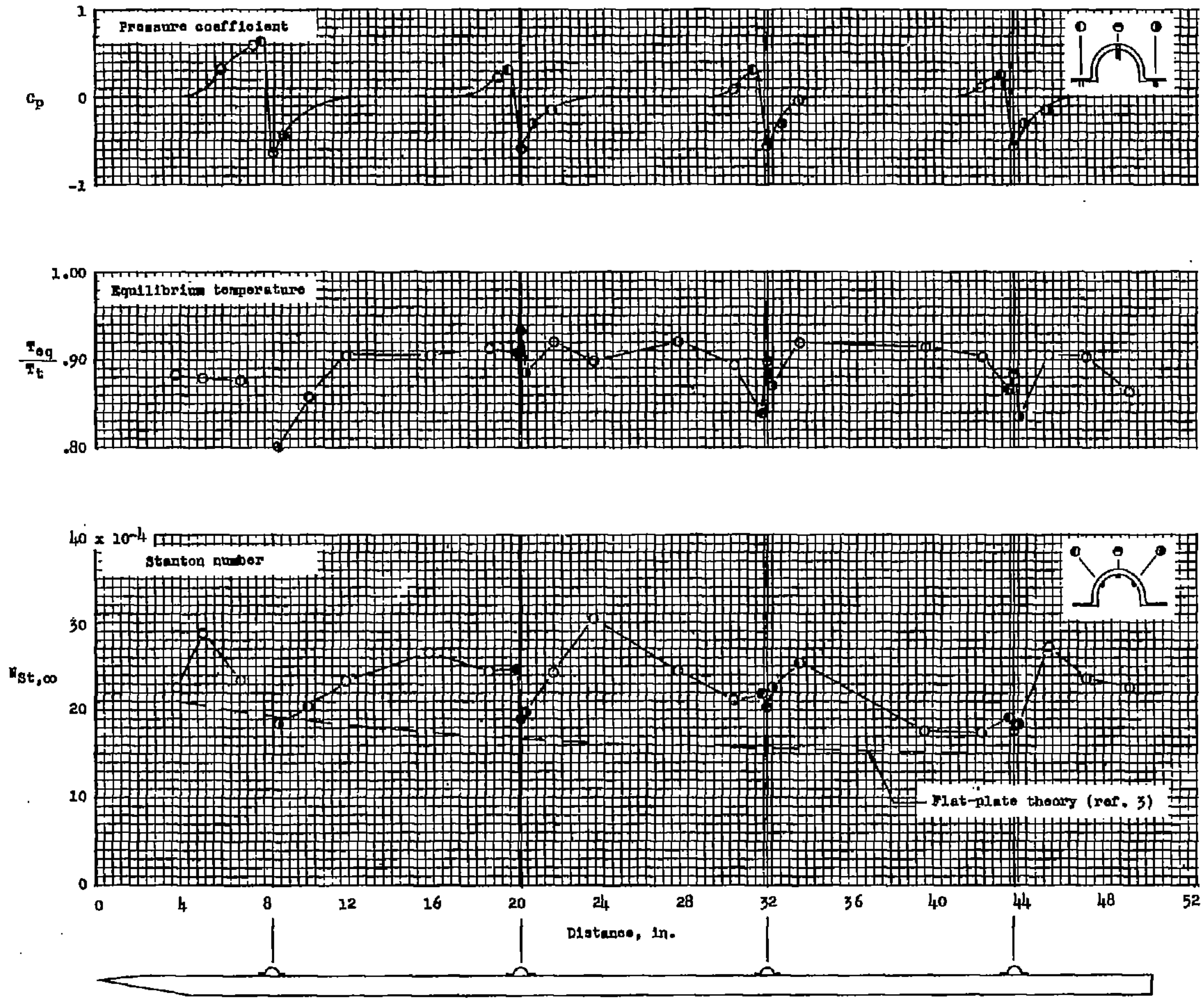

Figure 5.- Distribution of heat-transfer parameters and pressures for plate II at $M = 0.77$.

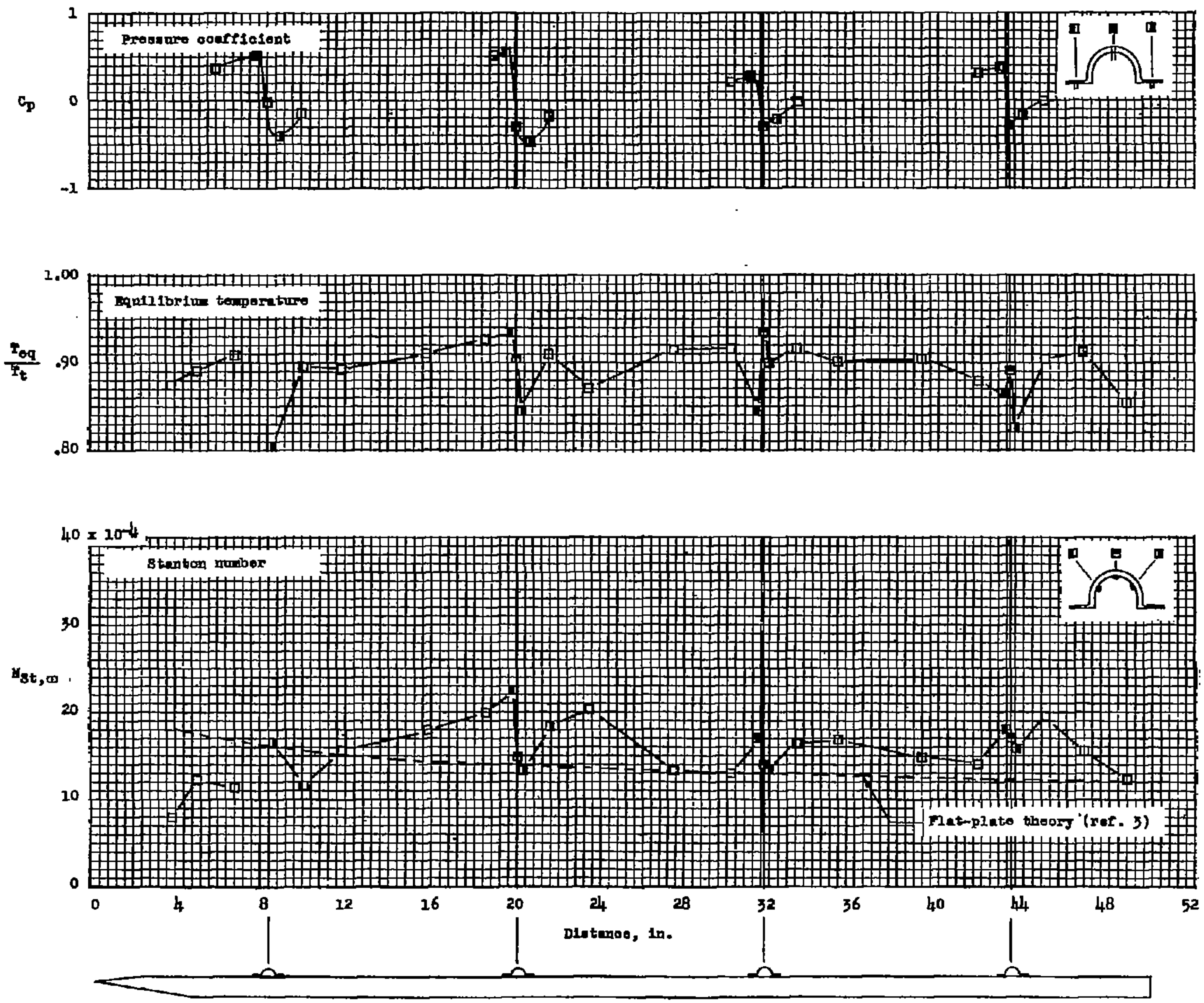

Figure 6.- Distribution of heat-transfer parameters and pressures for plate II at $M = 1.39$.

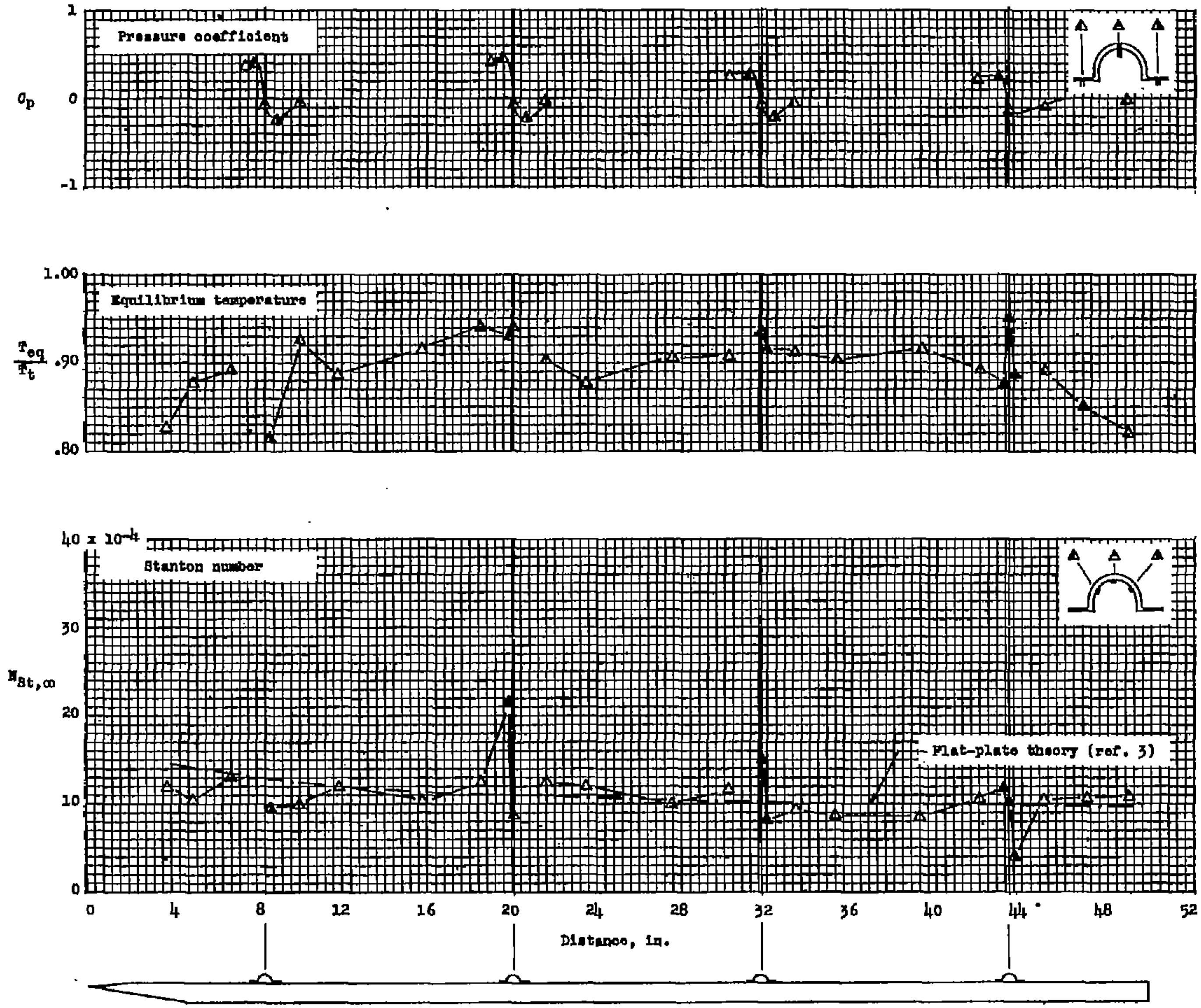

Figure 7.- Distribution of heat-transfer parameters and pressures for plate II at M = 1.98.

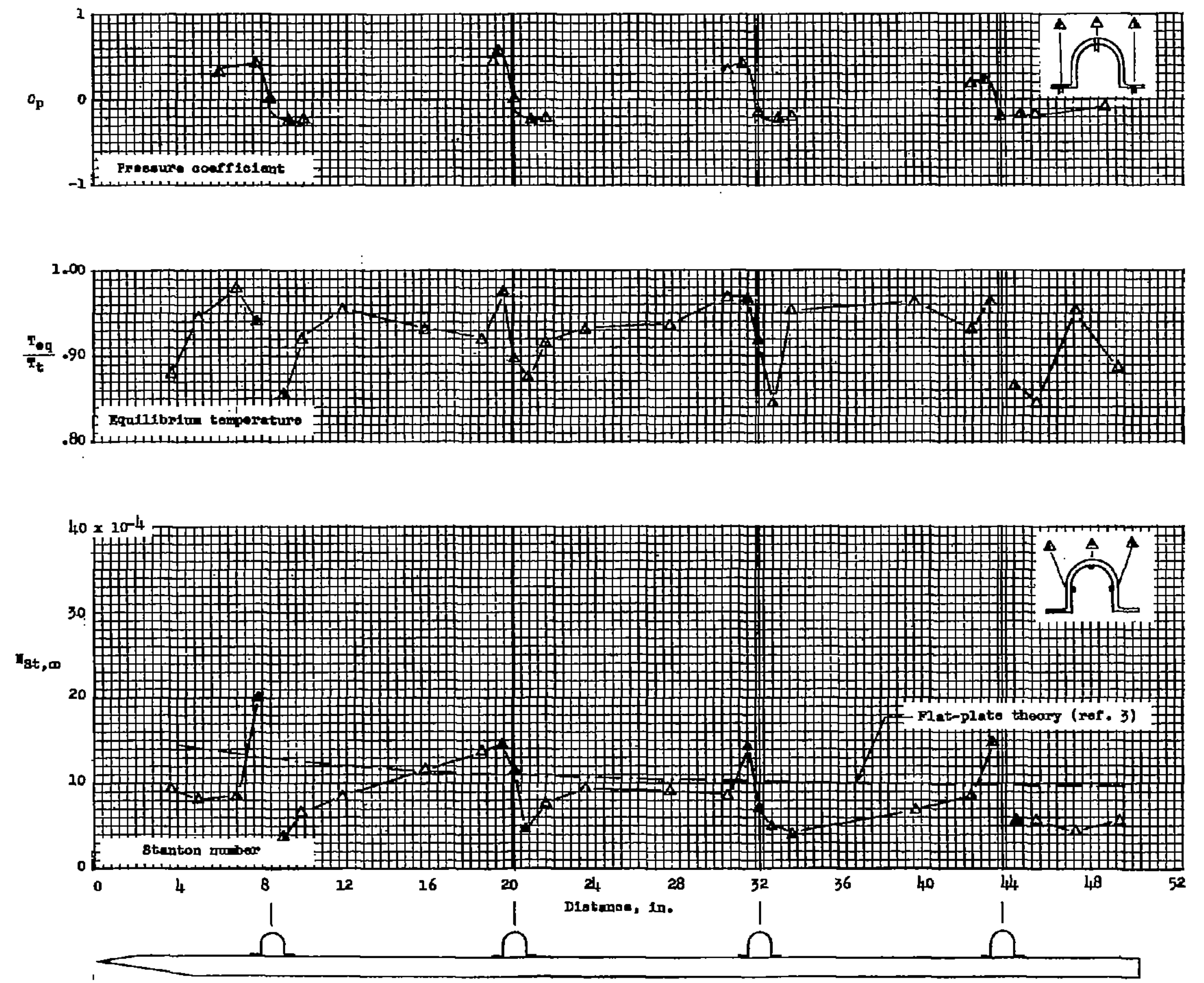

Figure 8.- Distribution of heat-transfer parameters and pressures for plate III at M = 1.98.

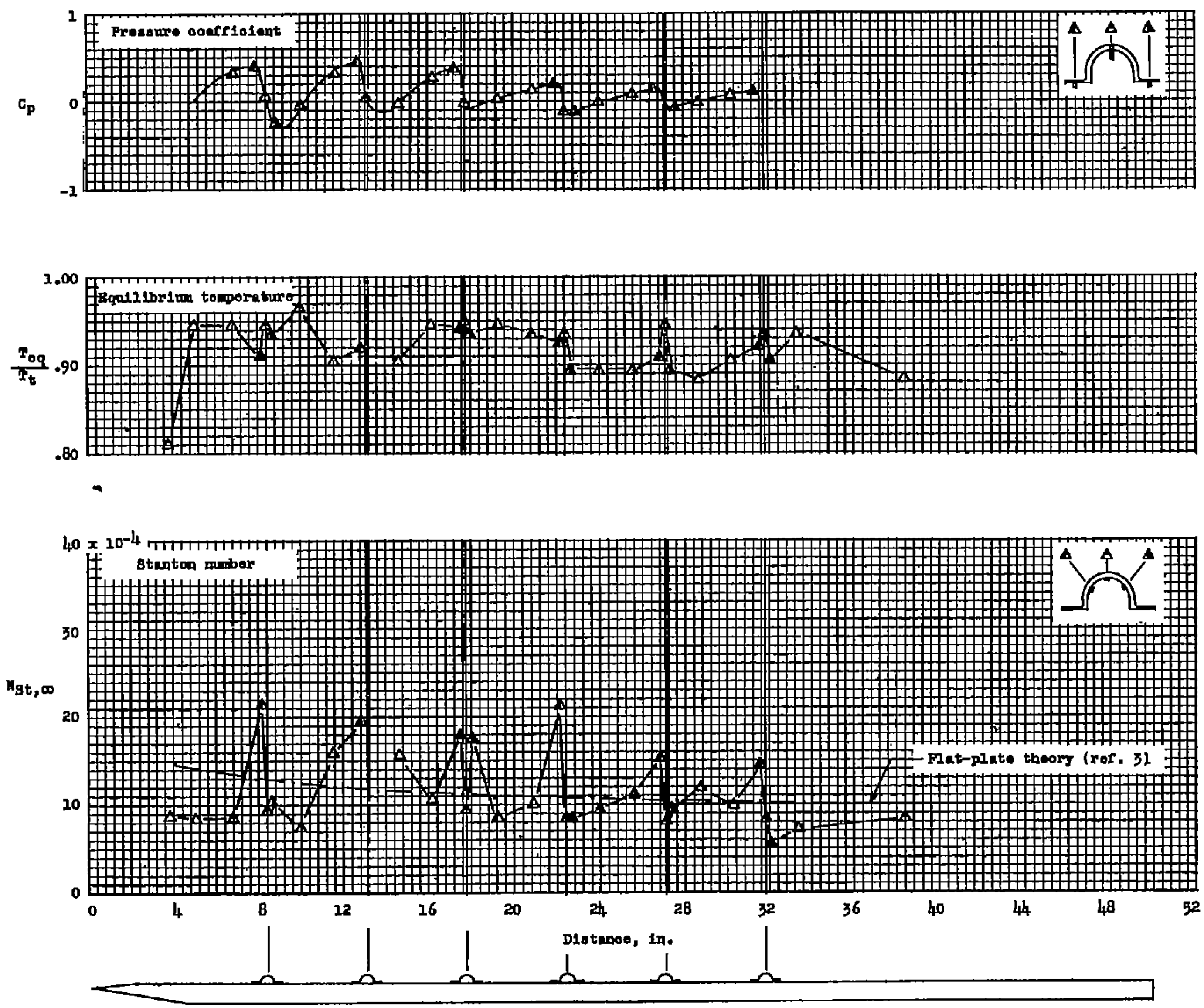

Figure 9.- Distribution of heat-transfer parameters and pressures for plate IV at $M = 1.98$.